Higgs Boson discovery at the LHC

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Outline

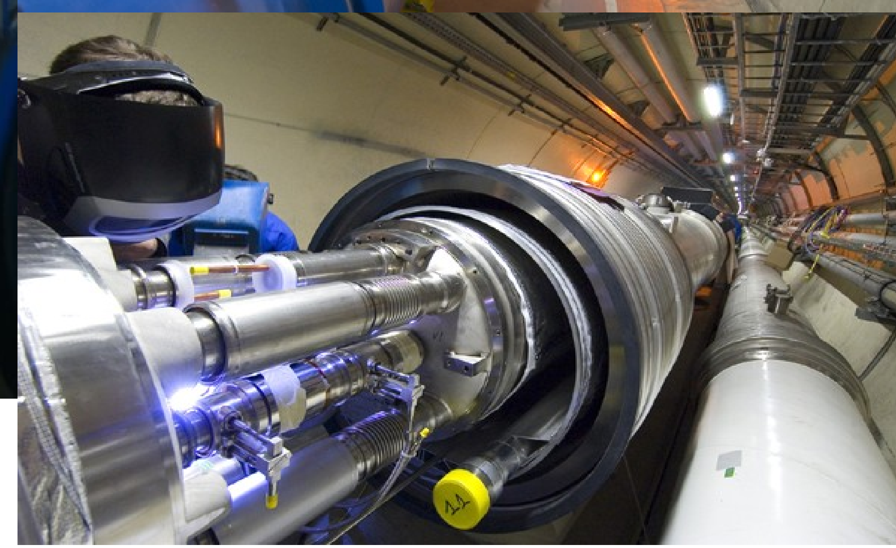
- Physics of the Higgs Boson at LHC
- Overview of the main inclusive discovery channels
  - $H \to \gamma\gamma$
  - $H \to ZZ \to 4l$
  - $H \to WW \to 2l2\nu$
- 2 brief examples of exclusive channels
  - t-t_bar H; $H \to bb$
  - q-q_bar H; $H \to WW \to \mu\nu q\bar{q}$
- Higgs properties measurement (Mass, Width, quantum numbers)

Disclaimer: results for CMS only (Physics TDR to appear soon)

LHC status

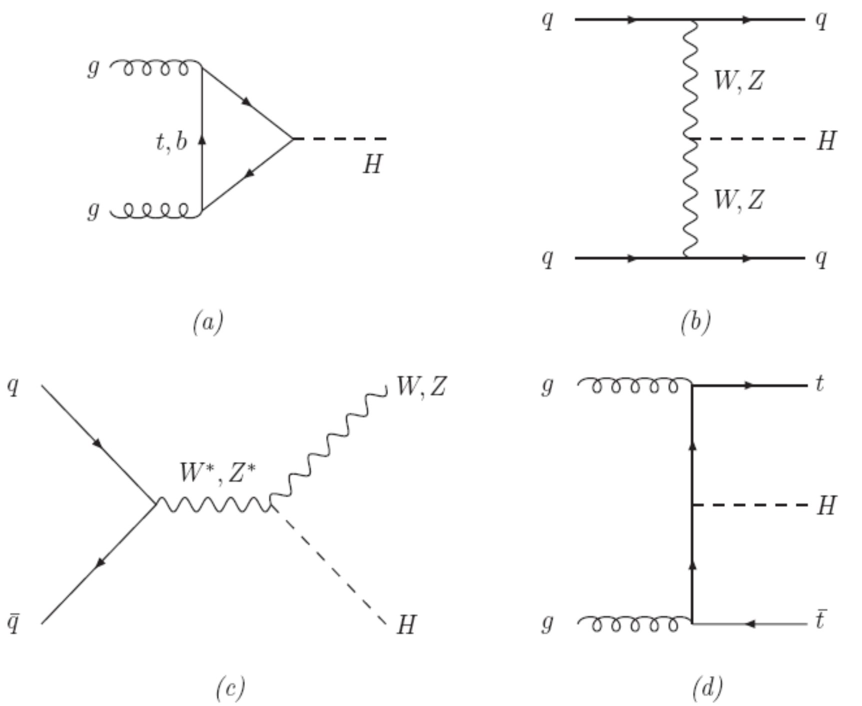
- No more so far to come
- Installation progressing well on schedule. Pilot run end 2007
- Integrated luminosity in 2008 (4 months) ~< 1 fb^{-1}

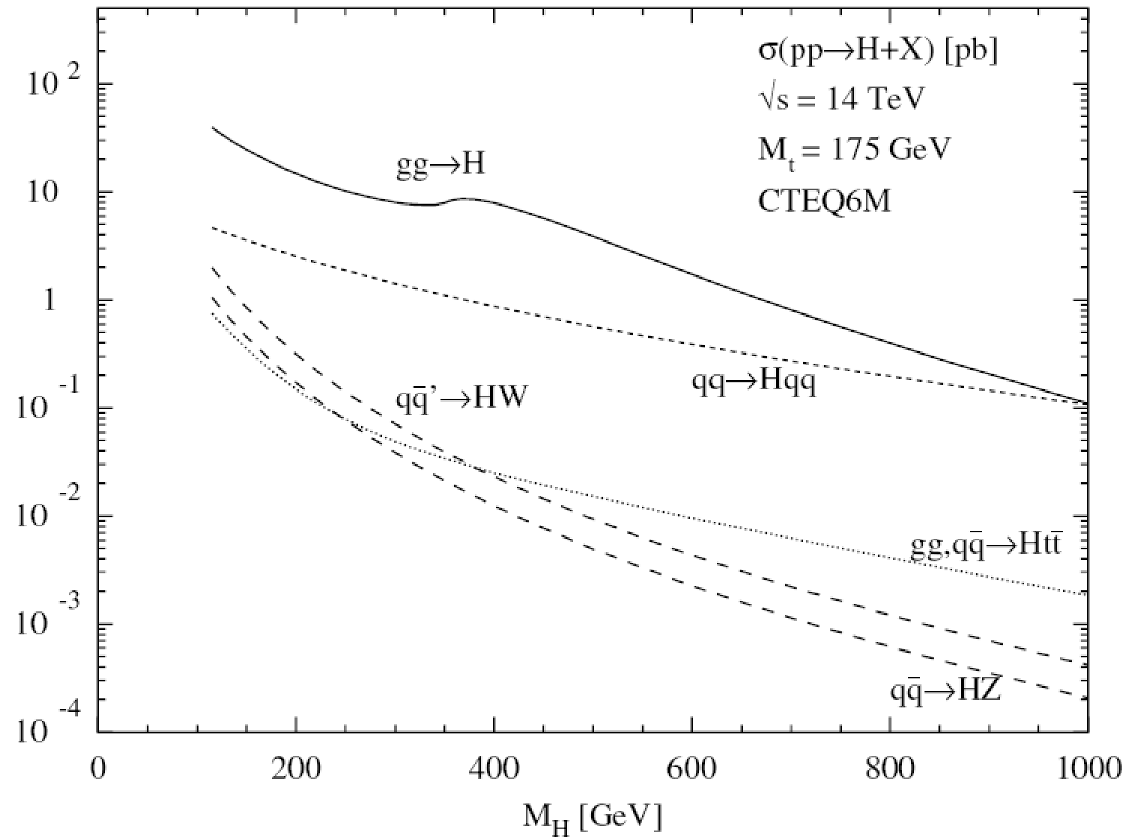





Higgs at LHC

Production

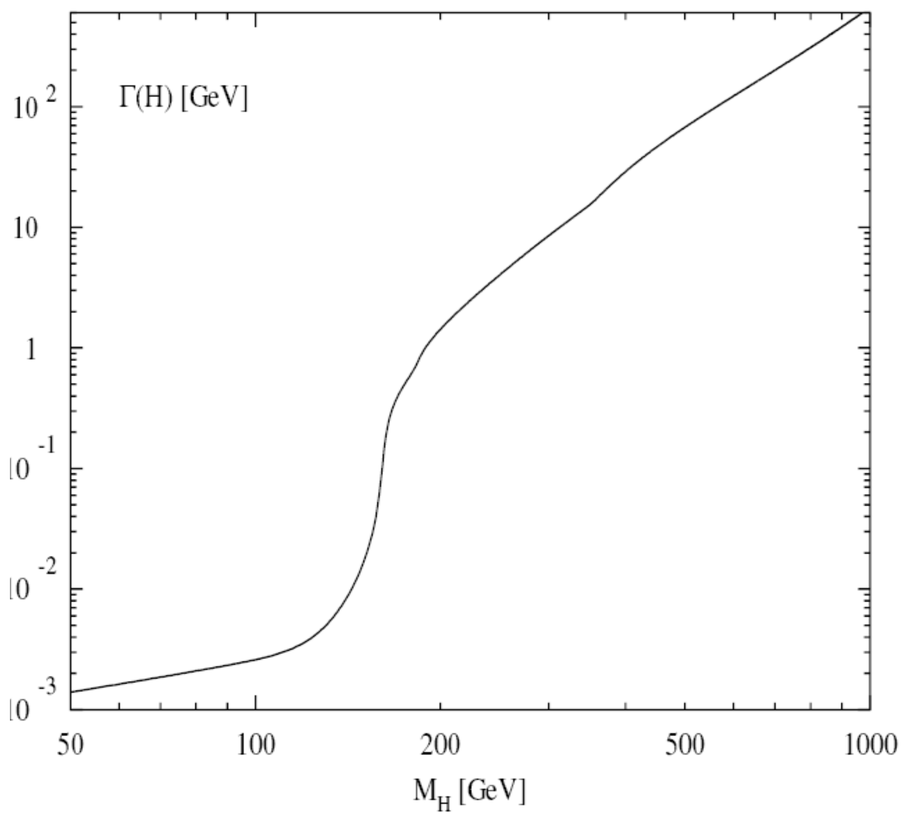


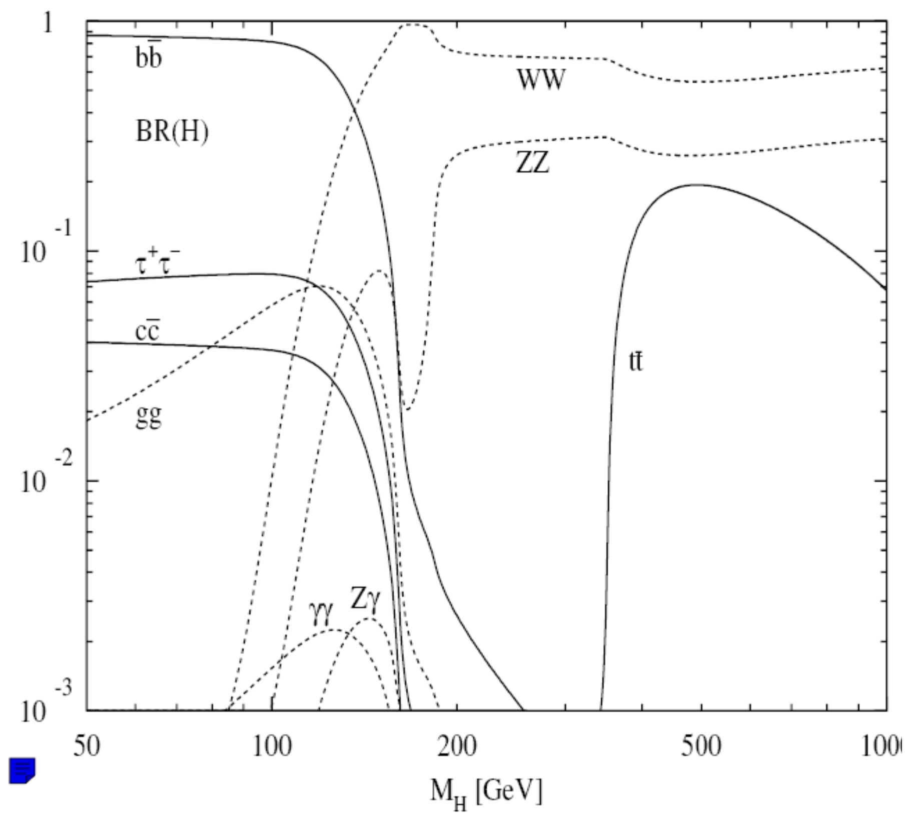


- gluon-gluon fusion main production mechanism in the whole mass range
- O(10) pb for $M_H < 200$ GeV => 1 Higgs every ~30sec at $2*10^{33} cm^{-2}s^{-1}$
- Vector Boson Fusion has sizable x-section. Important for Higgs coupling and for W-W scattering (unitary-violating ~ 800 GeV)
- t-t_bar associated production relevant at low M_H

Higgs at LHC

Decay





- b-b_bar dominates for low M_H (till M_H~130 Gev)
- WW dominant decay mode in the rest of the mass range
- ZZ opens up for M_H>~ $2M_Z$
- Γ_H < 1 GeV for M_H< 200 GeV, afterwards grows ~linearly with the mass (still a resonance?)

Higgs discovery channels

- At sqrt(s) O(100) GeV, QCD but also Electroweak processes have huge x-sections. Signal events are overwhelmed by the background.
- To isolate a phase-space region with mainly signal events (if possible) background rejection of $O(10^5)$ needed.

Main channels

- Mass range [115 , 130] GeV
  - $H \to \gamma\gamma$
- Mass range [130 , 150] and [180 , Λ]
  - $H \to ZZ \to 4l$ ($l=\mu$, e) golden channel
- Mass range [150 , 170] GeV
  - $H \to WW \to 2l2\nu$ ($l=\mu$, e) silver channel

- Exclusive (initial) final states can help in reducing the possible SM backgrounds:
  - t-t_bar H; H->bb or H->yy
  - q-q_bar H; $H \to WW \to \mu\nu q\bar{q}$; H->tt; . . .
- usually disfavored by the small x-section, by the difficult to predict contribution form SM background and detector performances

H->$\gamma\gamma$

- In the low mass range no hope for H->b-b_bar inclusive search
- Decay occurs via W, top and bottom loop. BR~2*10^{-3} till M_H<140
- σ*BR ranging between 100 and 70 fb between LEP limit (115) and 140 GeV

Backgrounds

- 2 real prompt photons (irreducible):
  - production via q-q_bar and gg with a box diagram
  - processes simulated at LO and renormalized with global K factor to NLO
- γ + jet (reducible)
  - the 2nd candidate from photon emitted during jet fragmentation or mis-identified jet or isolated π^0
- >2 jets (reducible)
  - both photon candidates from mis-measured jets
  - huge x-section. Difficult to simulate the needed statistics => cuts at generator level

$H \to \gamma\gamma$ Detector Issues

Calorimetry

- $H \to \gamma\gamma$ sets the most stringent requirements for electromagnetic calorimeter performances. Optimal energy resolution for M_H determination and granularity for π^0 suppression

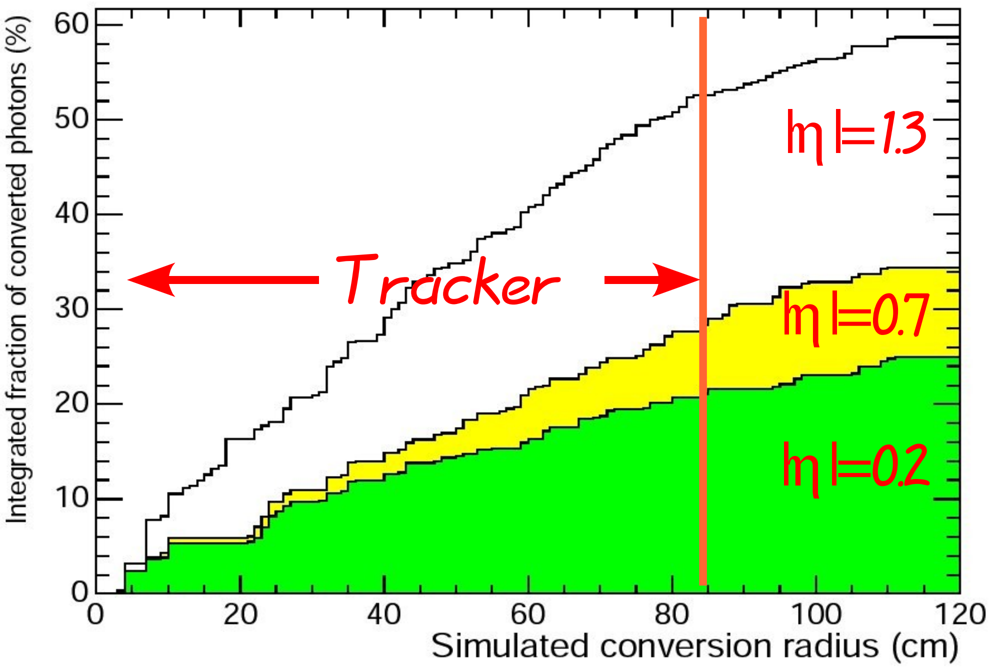
Primary Vertex

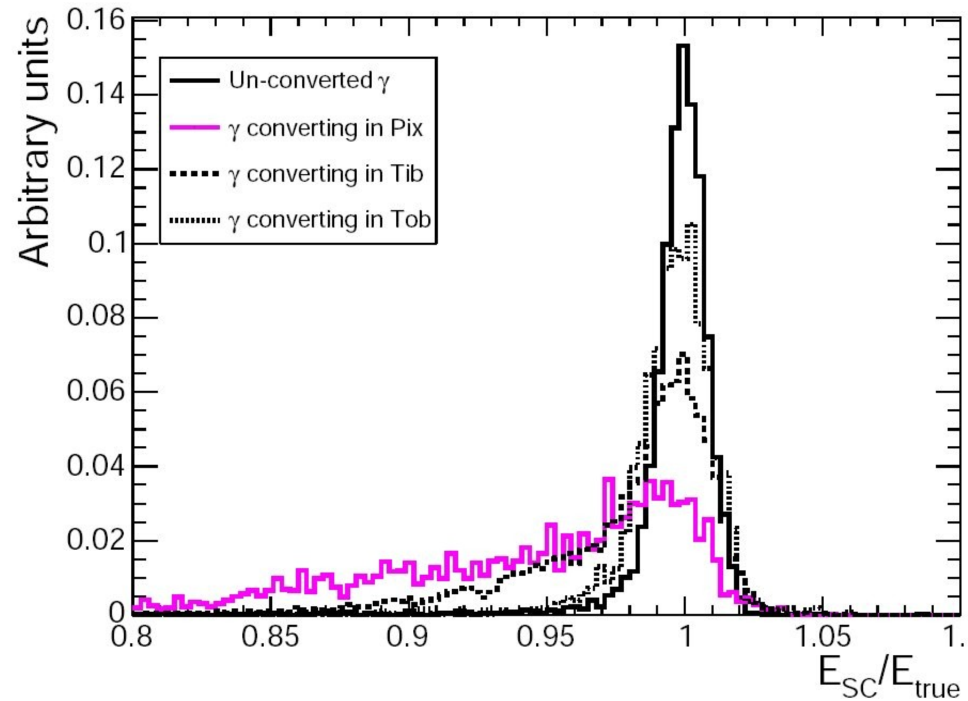
- At LHC the longitudinal spread of the interaction vertices is of 53 mm resulting in almost 2 GeV smearing in M_H resolution
- The hard scattering produces charged tracks with harder momentum than minimum bias interactions
- Tracking back those tracks allows to define the primary vertex with a 5mm precision in 83% of the signal events at low luminosity (warning for high lumi)

H->γγ Detector Issues

Photon Conversion

- Big amount of material before the Electromagnetic calorimeter
- High probability of the photon to convert into e^+e^- pairs before reaching the E-cal => M resolution spoiled!

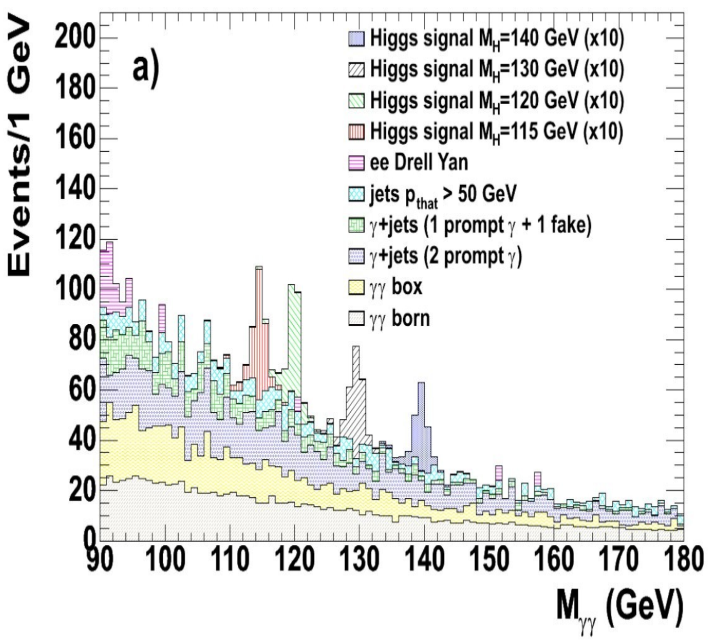


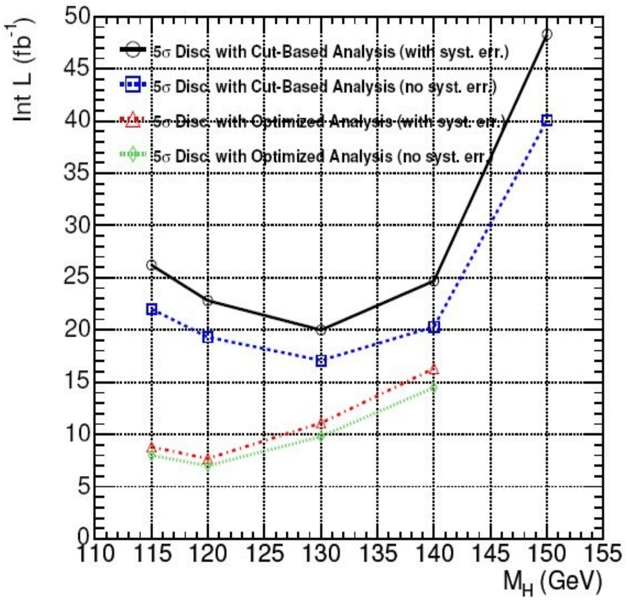


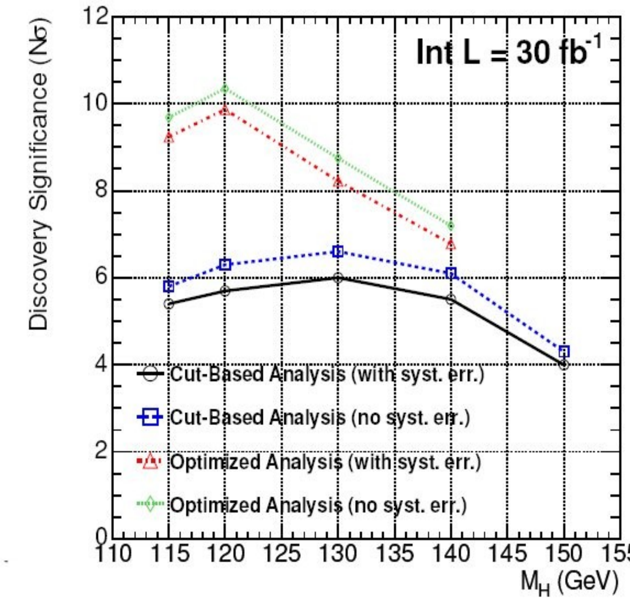
- Tracker itself used to reconstruct the e^+e^- pairs and to recover the photon energy resolution

H->γγ Analysis and Results

- Two approaches:
  - Standard cut-based analysis (photons' Et and isolation) applied to different |η| regions
  - Neural Network optimized analysis profiting of the different signal-background kinematics and photon candidate isolation
- Background estimation from sidebands. Systematic error from the predicted shape, statistics uncertainty from the mass range to perform the fit on



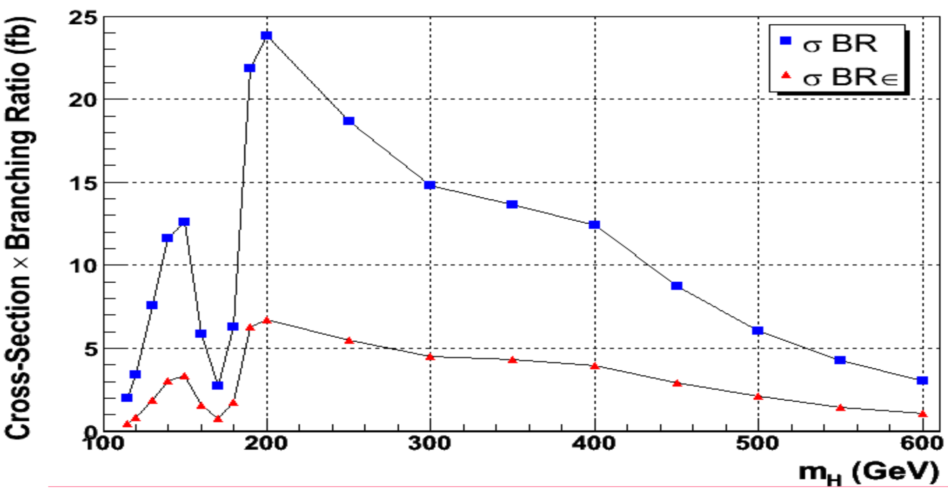




- At low luminosity 25 fb^{-1} are needed for discovery in the range 115-140 GeV. Less then 15 fb could be sufficient for the optimized analysis
- ~5 fb sufficient to exclude at 95% CL

H->ZZ->4l

- muons (cleanest), electrons and combinations (double x-sec) considered as possible final states. Signal produced at LO and reweighted at NLO with $K(Pt_H)$. Further enhancement due to interference of permutation of identical fermions from different Z's (15% at low MH).
- Backgrounds:
  - Z/γ–Z/γ (irreducible). Generated with CompHEP (t and s channels) and reweighted with K(MH) to NLO (MCFM). gg->ZZ also included
  - Z/γ–b-b_bar. Generated with CompHEP (gg and qqbar initial state) and reweighted with constant K to NLO (MCFM)
  - t-t_bar. NLO x-sec (840 pb) used
- Other processes as bbbb, bbcc, cccc, single-top Z-cc, Wbb, Wcc demonstrated to be negligible



2e 2μ final state

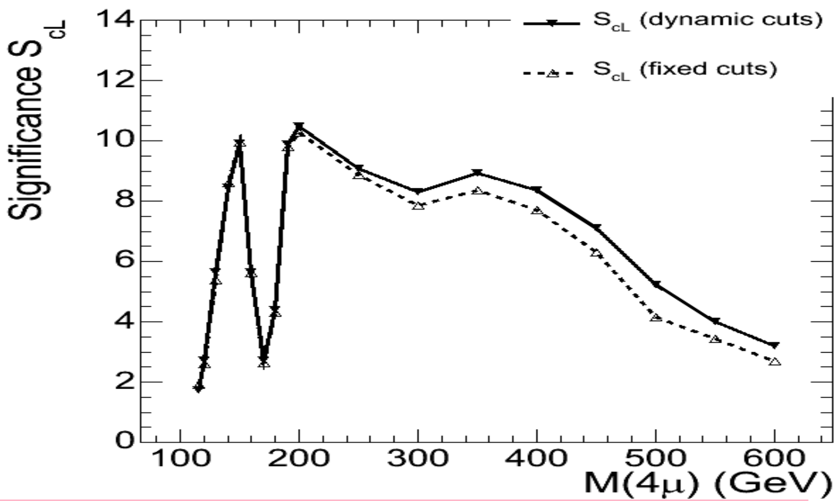
	tt	Zbb	ZZ
σ (fb)	$840x10^3$	$555x10^3$	$28.9x10^3$
σ.BR.ε (fb)	744	390	37.0

H->ZZ->4l

Selections and Search strategies

- Cleanest signal possible: 4 isolated, high Pt leptons pointing to the same primary vertex with at least two lepton with $M_{ll} \sim M_Z$
- Two selections strategies:
  - M_H independent cuts (all analysis): to reduce systematic uncertainties and MC dependence
  - M_H dependent cuts (4μ final state): M_{4l} is the most discriminating variable => Optimization only on isolation, Pt of the 3rd μ and window M_{4l}
- In both cases only ZZ->4l remains as important background the others beeing negligible
- All analysis use to discriminate the presence of the signal the significance estimator(s) based on log-likelihood ratio

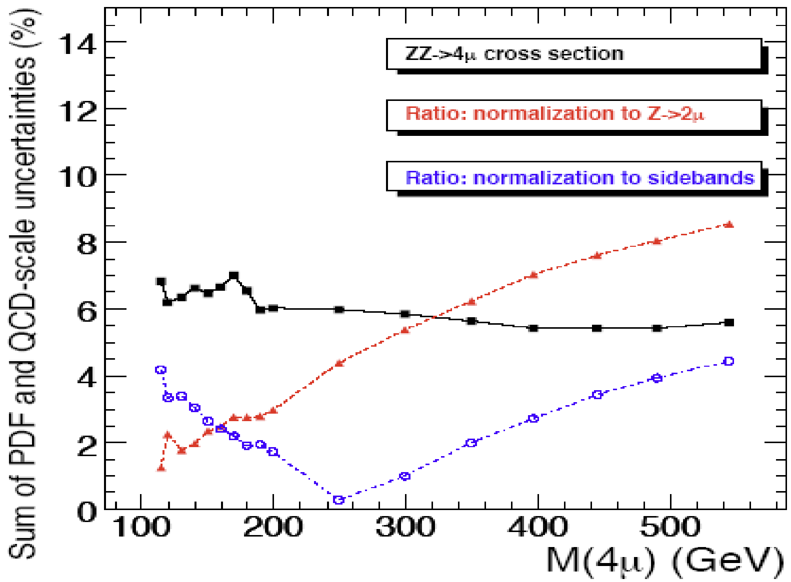
$$S_L = \sqrt{-2 \ln Q} \quad \text{where} \quad Q = \left(1 + \frac{N_s}{N_b}\right)^{N_s + N_b} e^{-N_s}$$



H->ZZ->4l

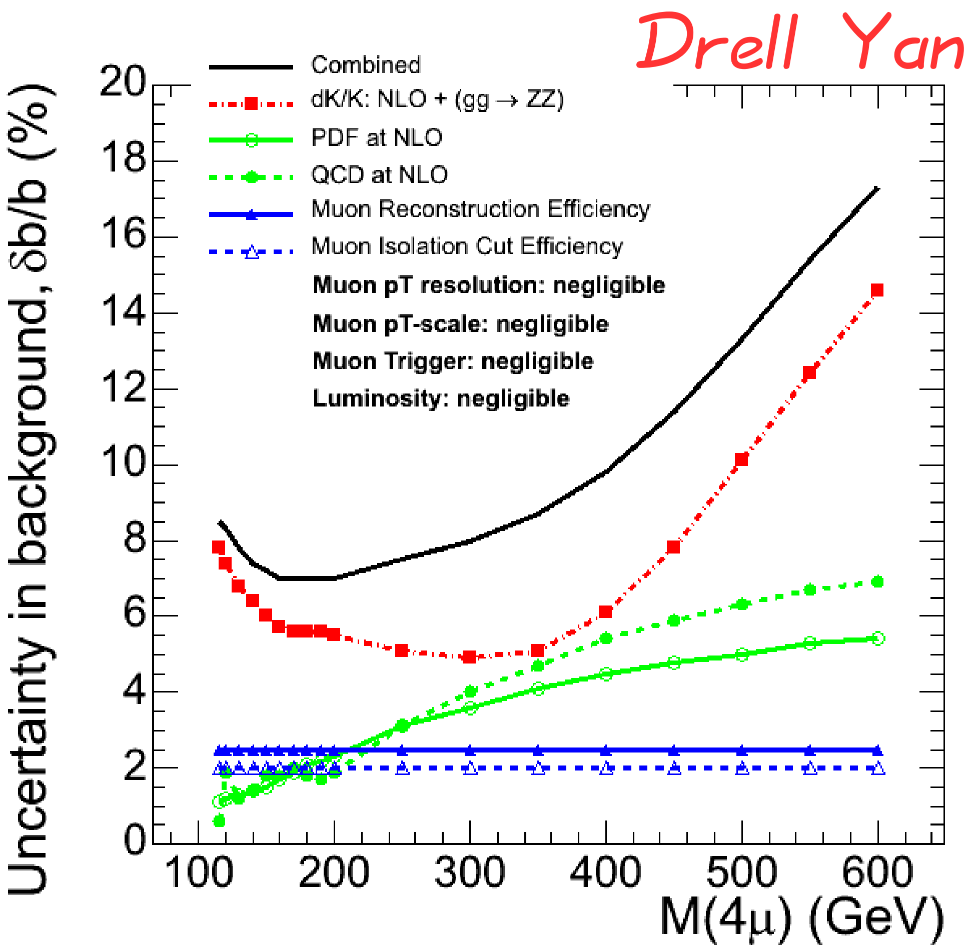
Systematics on ZZ->4l

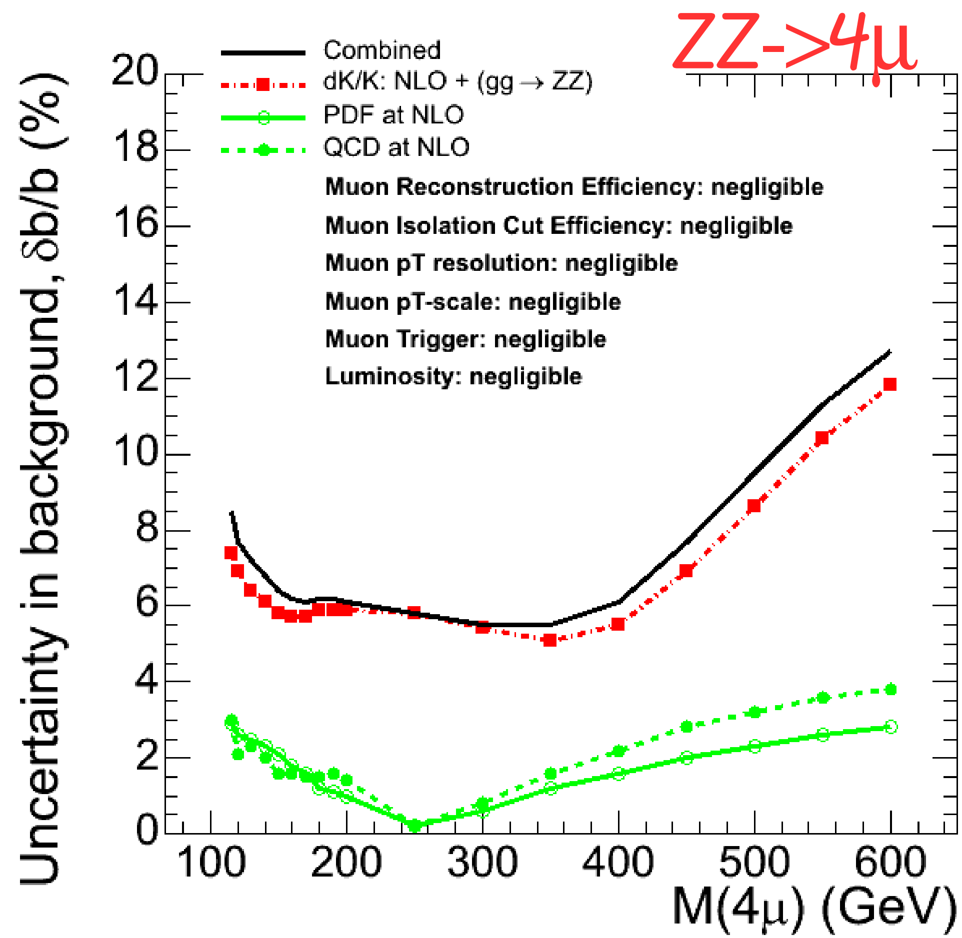
- Sources:
  - PDF and QCD scale
  - NLO vs LO dynamics
  - Isolation efficiency
  - Reconstruction efficiency (only for electrons)
  - Energy/Momentum Scale
  - Identification (charge)
- Normalization from data compulsory. Two control samples:
  - Drell Yan (no statistical limitation)
  - M_H sidebands (reduces NLO-LO uncertainties, pays low statistics)



H->ZZ->4l

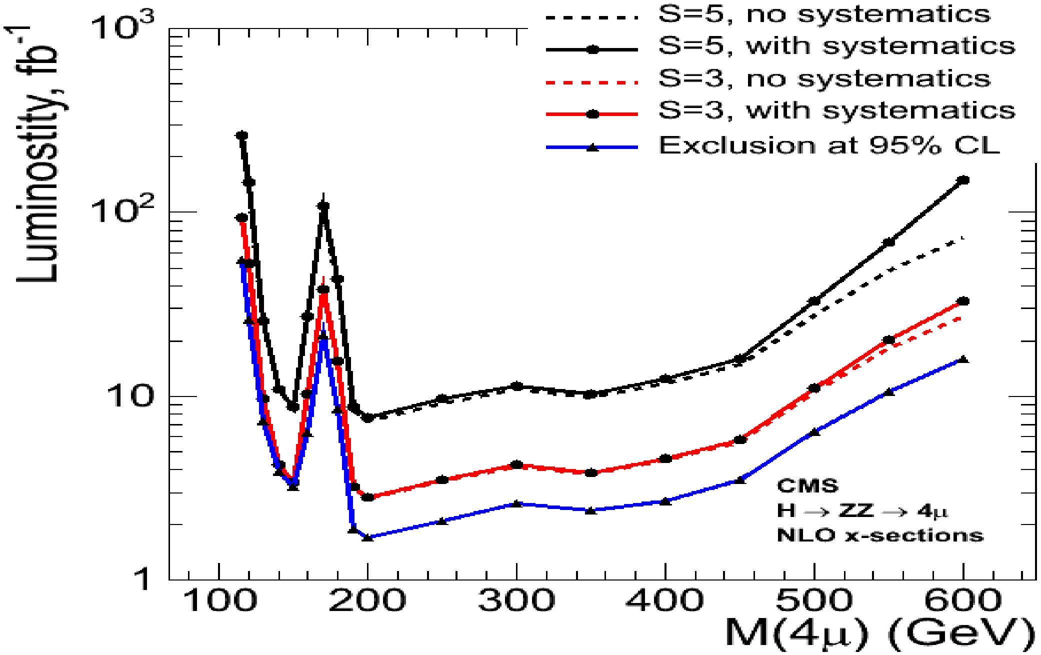
Systematics for 4μ final state

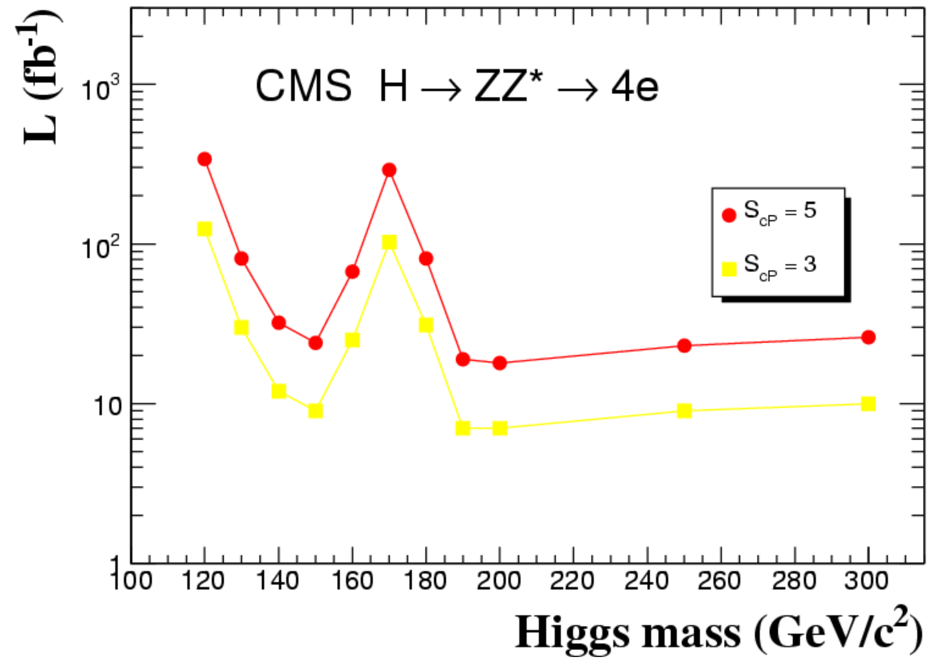


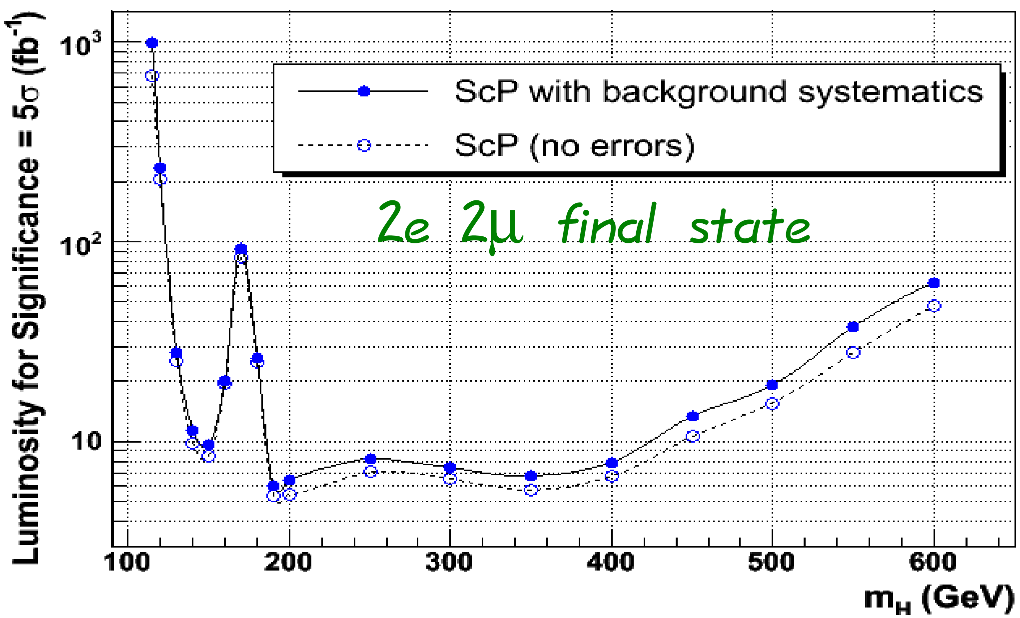


H->ZZ->4l

Results







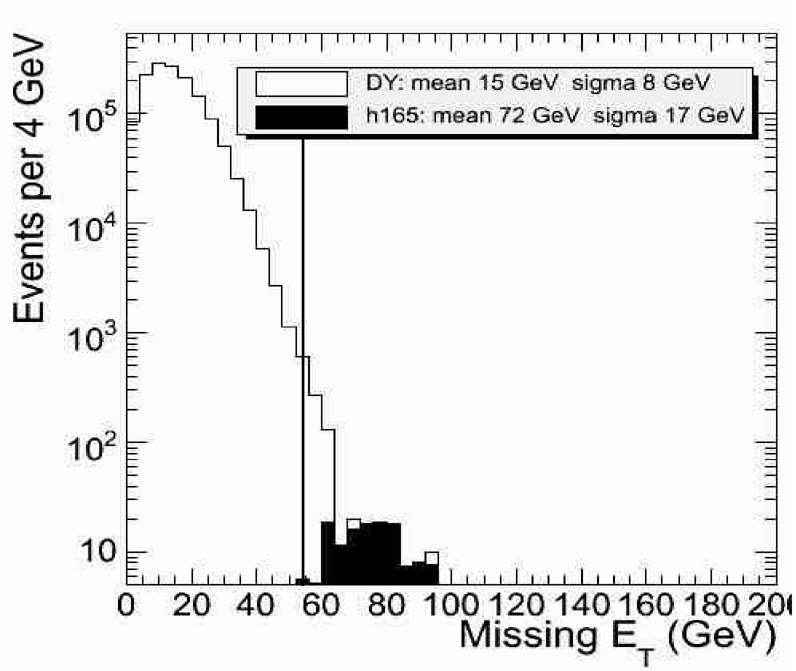
- combining the final states:
  - exclusion in almost the full mass range with ~1 fb^{-1}
  - discovery for M_H>~ $2M_Z$ with ~5 fb^{-1}. For M_H in [140-150] 10 could be sufficient

H->WW->2l2ν

- Extremely clean signal: 2 isolated high Pt leptons pointing to the same primary vertex, "high" Missing Et and NOTHING else in the detector
- High x-sec*BR but NO Invariant mass peak!
- Main backgrounds:
  - WW. irreducible. Reweighted by NLO Pt_{WW}. gg->WW also simulated
  - t-t_bar. reduced by jet veto. NLO x-sec (840 pb) used
  - Single top (Wt final state). Non trivial to separate from t-t_bar
  - Drell Yan. in the case of same flavor final state, reduced by M_{ll} and MEt
  - WZ, ZZ->2l, b-b_bar negligible
- Discriminating variable is the opening angle between the 2 leptons (scalar nature of the Higgs + V-A structure of weak interactions). Spin correlation in the simulation matters!
- The viability of the channel depends on the possibility to evaluate each background contribution from the data

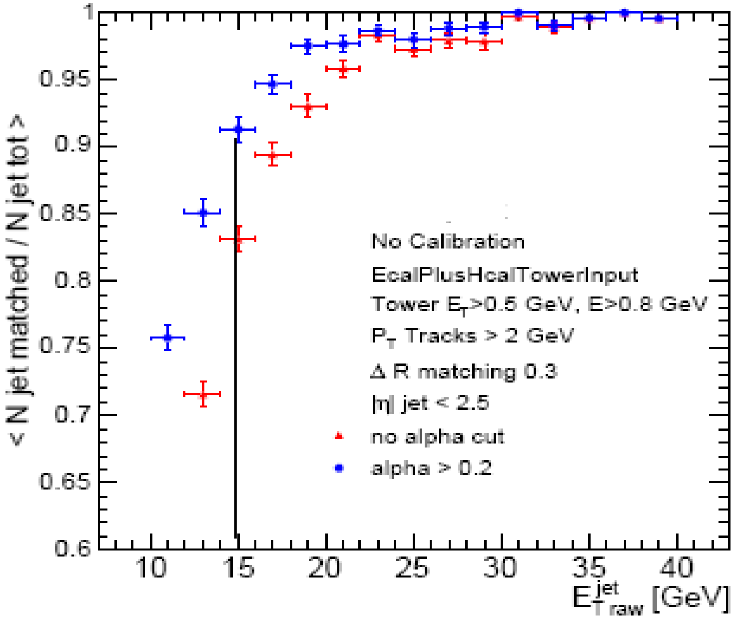
H->WW->2l2ν Detector Issues

- At the LHC the MEt is never 0. Long tail even in clean events like DY+0 jets. Need to normalize MEt measurement directly on data, best candidate Z boson



- Vetoing the jets is an extremely delicate task: difficult to define a jet at low Et and high rapidity. Tracker information used to reduce fake rate:

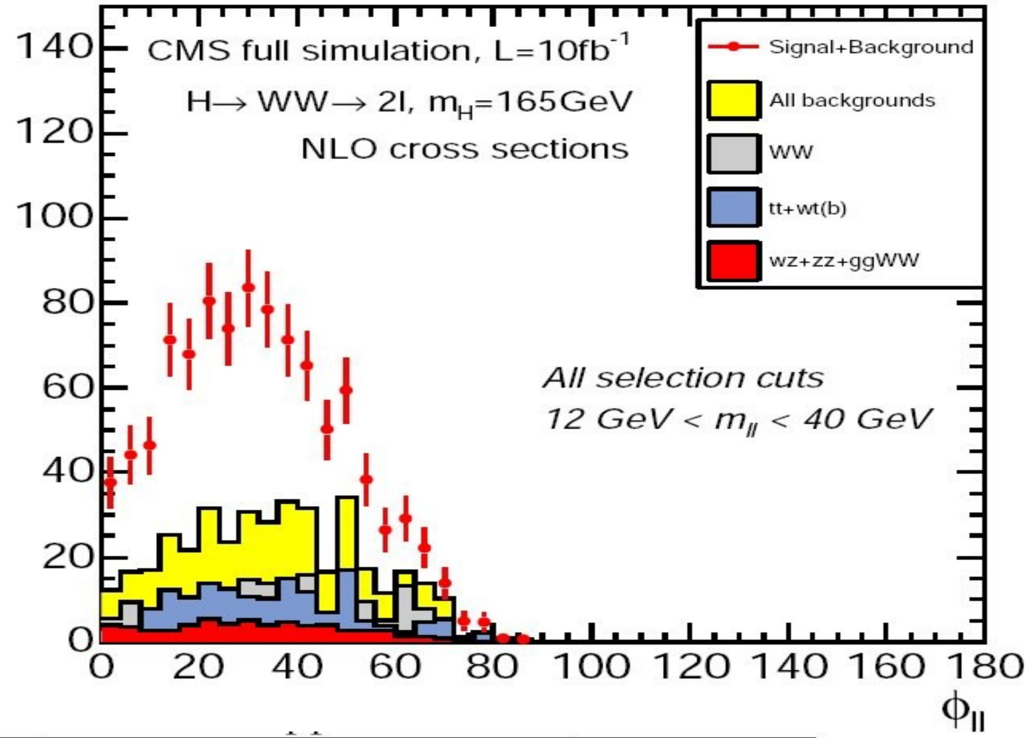
$$\alpha = \frac{\sum_{sel.tracks} p_T}{E_T(jet)}$$



H->WW->2l2ν

Selections

- Squeezing to the signal phase space:
  - lepton id (#, charge, isolation)
  - Vertex constrain
  - lepton Pt
  - M_{ll} cut
  - MET
  - Jet Veto
  - ϕ_{ll}



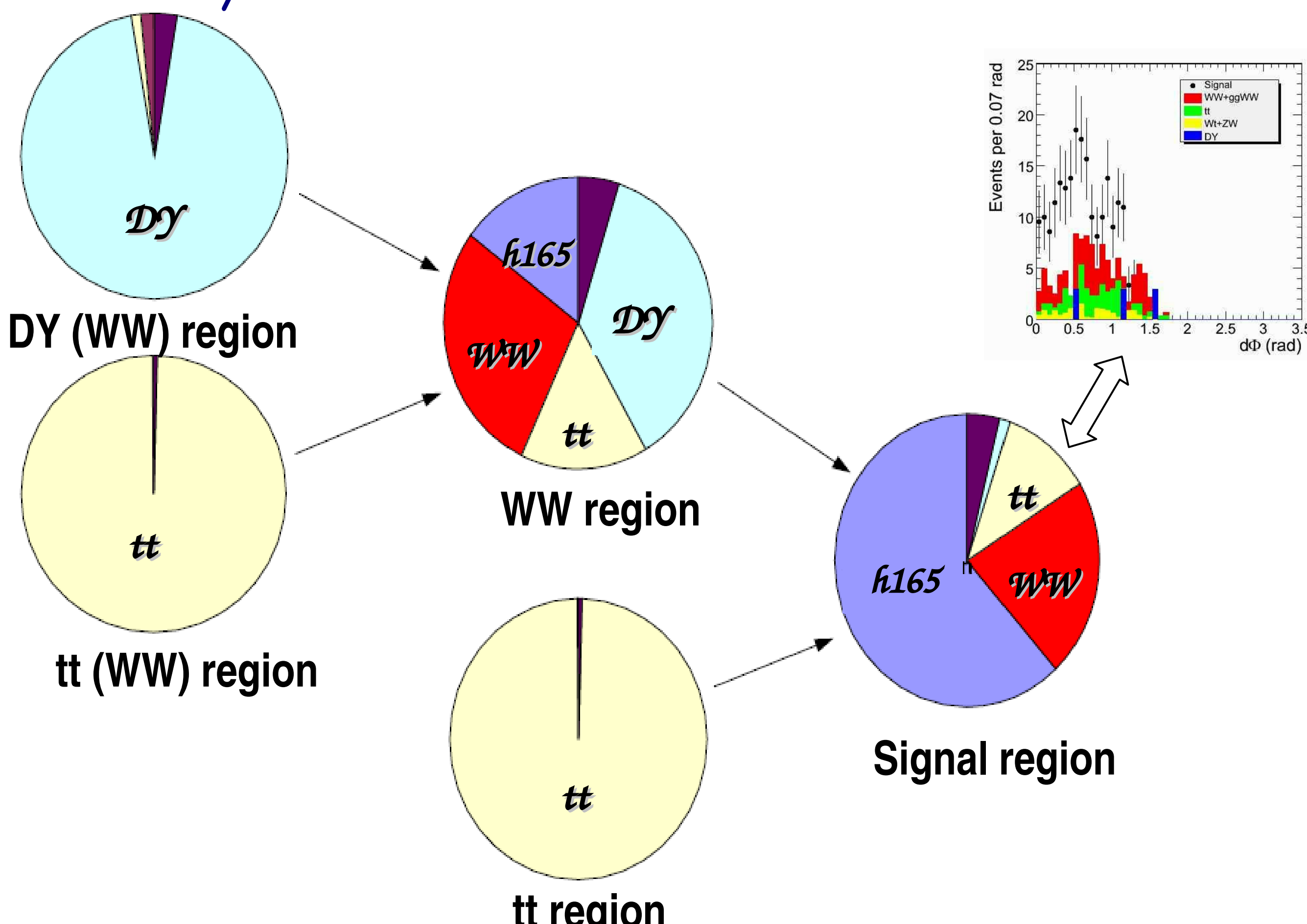
Reaction pp → X	$\sigma_{NLO} \times$ BR	L1+HLT	2 leptons	All cuts
$\ell = e, \mu, \tau$	pb	Expected event rate in fb		
$H \to WW \to \ell\ell$, $m_H = 160$ GeV	2.34	1353 (58%)	359 (27%)	42 (12%)
$H \to WW \to \ell\ell$, $m_H = 165$ GeV	2.36	1390 (59%)	393 (28%)	46 (12%)
$H \to WW \to \ell\ell$, $m_H = 170$ GeV	2.26	1350 (60%)	376 (28%)	33 (8.8%)
$qq \to WW \to \ell\ell$	11.7	6040 (52%)	1400 (23%)	12 (0.9%)
$gg \to WW \to \ell\ell$	0.48	286 (60%)	73 (26%)	3.7 (5.1%)
$tt \to WWbb \to \ell\ell$	86.2	57400 (67%)	15700 (27%)	9.8 (0.06%)
$tWb \to WWb(b) \to \ell\ell$	3.4	2320 (68%)	676 (29%)	1.4 (0.2%)
$ZW \to \ell\ell\ell$	1.6	1062 (66%)	247 (23%)	0.50 (0.2%)
$ZZ \to \ell\ell, \nu\nu$	1.5	485 (32%)	163 (34%)	0.35 (0.2%)
Sum backgrounds	105	67600 (64%)	18300 (27%)	28 (0.2%)

H->WW->2l2ν

Backgrounds normalization

- Compulsory to rely on data to get background contribution in the signal region. A control phase space region for each background eventually with sub-control regions (e.g. for WW)
- The uncertainties on the extrapolated number of background events set the amount of integrated luminosity needed

Normalization schema for $2\mu 2\nu$ final state



H->WW->2l2ν

t-t_bar background normalization (example)

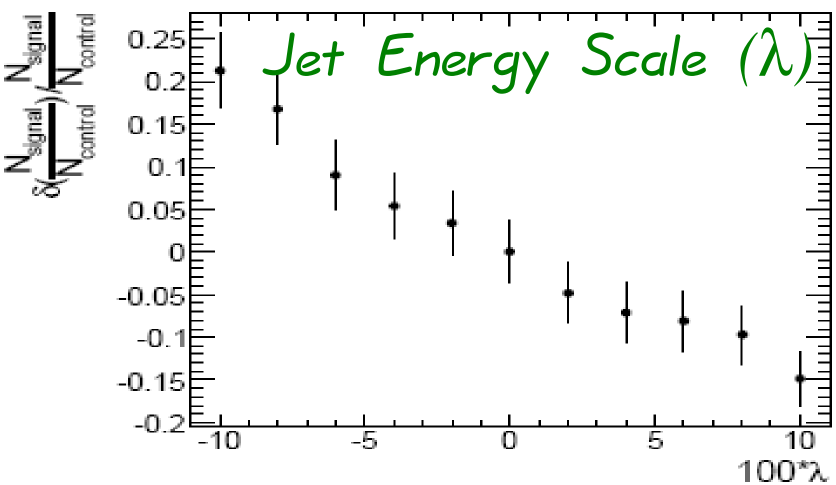
- Control region defined by the same selections as for the signal region but the jet veto. 2 b-tagged jets are required in addition
- The procedure relies on the relation:

$$N_{signal_{reg}} = \frac{N^{MC}_{signal_{reg}}}{N^{MC}_{control_{reg}}} N_{control_{reg}} = \frac{\sigma^{MC}_{signal_{reg}}}{\sigma^{MC}_{control_{reg}}} \frac{\varepsilon^{MC}_{signal_{reg}}}{\varepsilon^{MC}_{control_{reg}}} N_{control_{reg}}$$

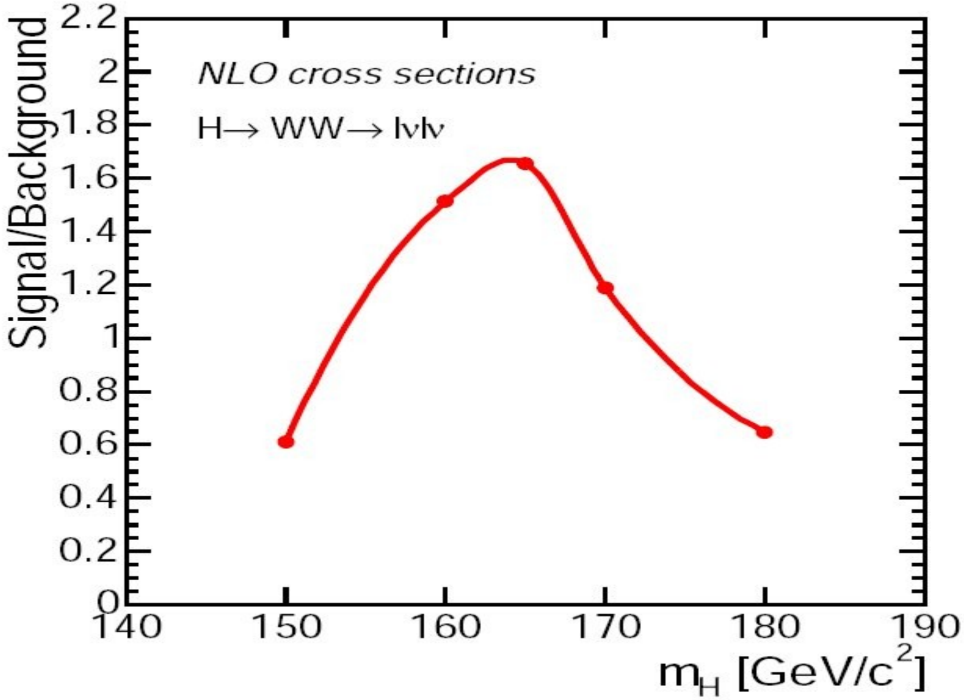
	Theor. Error	Detector systematics			Stat. Error	Total Error
		JES	α crit.	b-tagging		
($L = 1\ fb^{-1}$)	10 %	10 %	4 %	11 %	24 %	30 %
($L = 5\ fb^{-1}$)	10 %	6 %	4 %	9 %	11 %	19 %

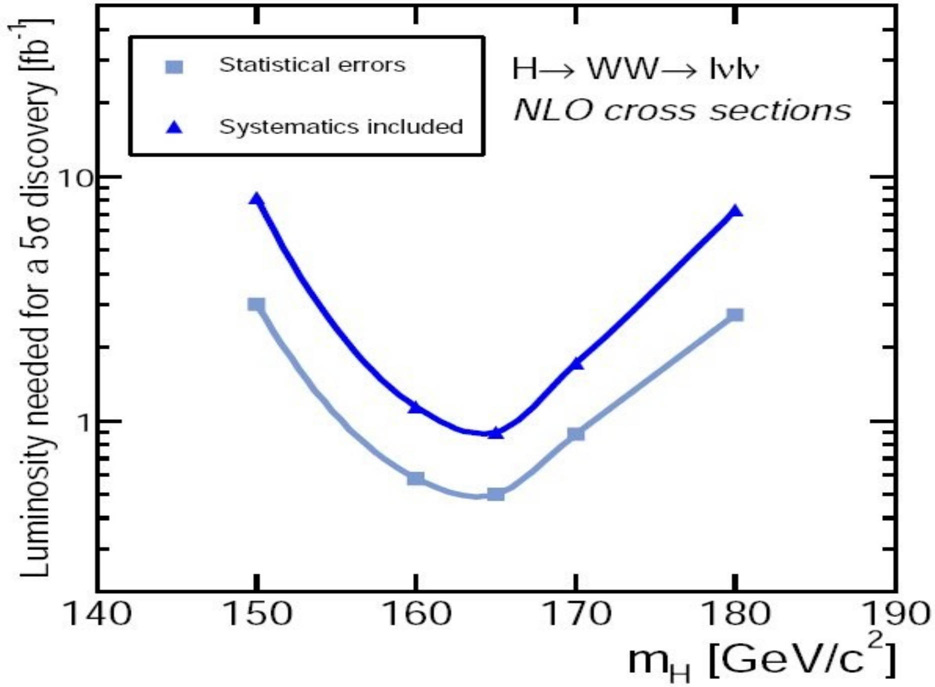
($L = 1\ fb^{-1}$)

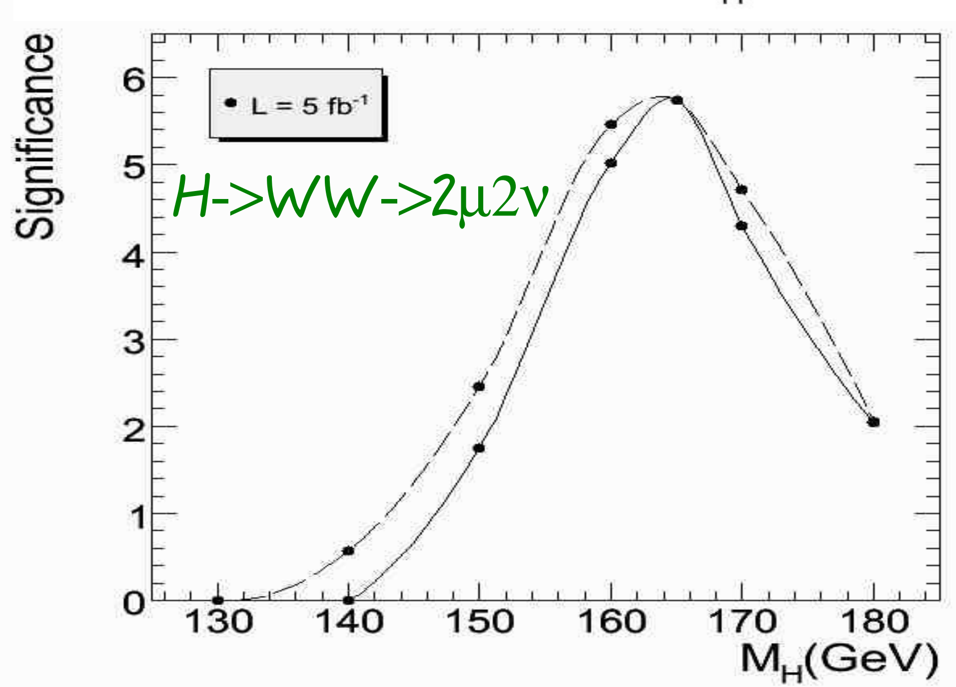
Channel	Signal region	$t\bar{t}$ region
Signal	14.3	0.0
$t\bar{t}$	2.6	17.0
WW	5.1	0.0
DY	0.3	0.0
Wt,ZZ,WZ	0.8	0.1
all	23.1	17.1



H->WW->2l2ν Results



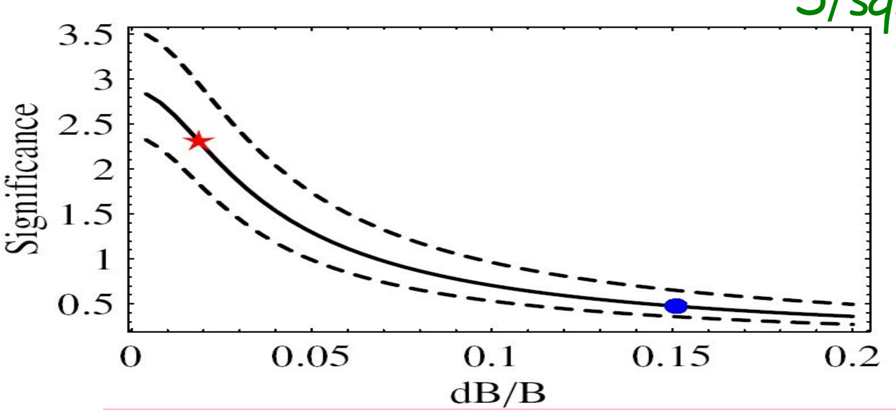




- High(est) discovery potential: If M_H = 165 GeV, only ~1 fb^{-1} may be needed
- Pay attention to the high number of experimental and theoretical systematics in the game.
- No mass measurement method yet available

ttH; H->b-b_bar

- Extremely exclusive signature suitable for low M_H, disfavored by the low x-sec
- 3 final states taken in consideration:
  - H->bb_bar, t_bar->μ/e ν b, t->μ/e ν b (fully leptonic)
  - H->bb_bar, t->bqq_bar, t_bar->μ/e ν b_bar (semileptonic)
  - H->bb_bar, t->bqq_bar, t_bar->b_bar qq (fully leptonic)
- In all cases many jets in the event. Background coming also from the wrong jets combinatorial
- Major backgrounds from ttbb, Ztt, tt+Njets and multijets QCD events
- Major problem is the normalization of the background from data: Anti b-tag methods used to select ttNjets background w/o signal contribution
- Many sources of uncertainty: manly MC predictions, Jet Energy Scale and b-tagging efficiency. These systematics (too pessimistic?) kill the signal.



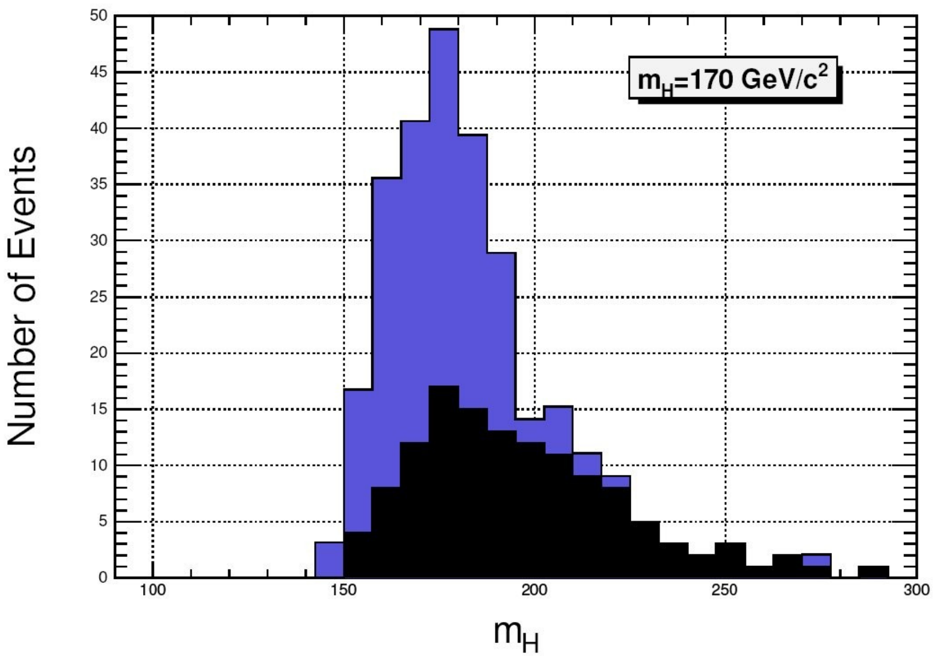
S/sqrt(B) for 60 fb^{-1}

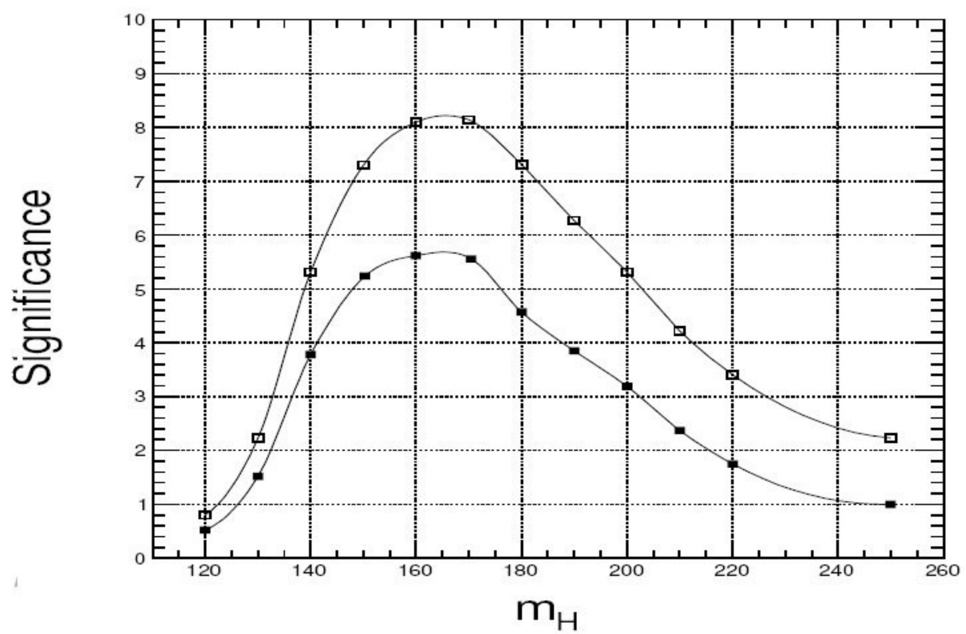
	Mh=115	Mh=120	Mh=130
fully leptonic	1.76	1.39	0.86
semi leptonic (mu)	2.4	1.9	1.3
semi leptonic (e)	1.7	1.4	0.86
fully hadronic	2.61	2.37	1.61

q-q_bar H; H->WW->lνq-q_bar

- Exclusive signature suitable for M_H, ranging between 120 and high masses, characterized by two forward tagging jets
- Like inclusive H->WW but with hadronic W => Higgs mass
- Backgrounds from tt+Njets, W(W)+jets and QCD
- To extrapolate the selection efficiency for QCD events, the selections are factorized into 3 groups and each group's efficiency measured directly from data
- Main systematics from Jet energy scale and resolution, MEt resolution and lepton isolation (~15%)

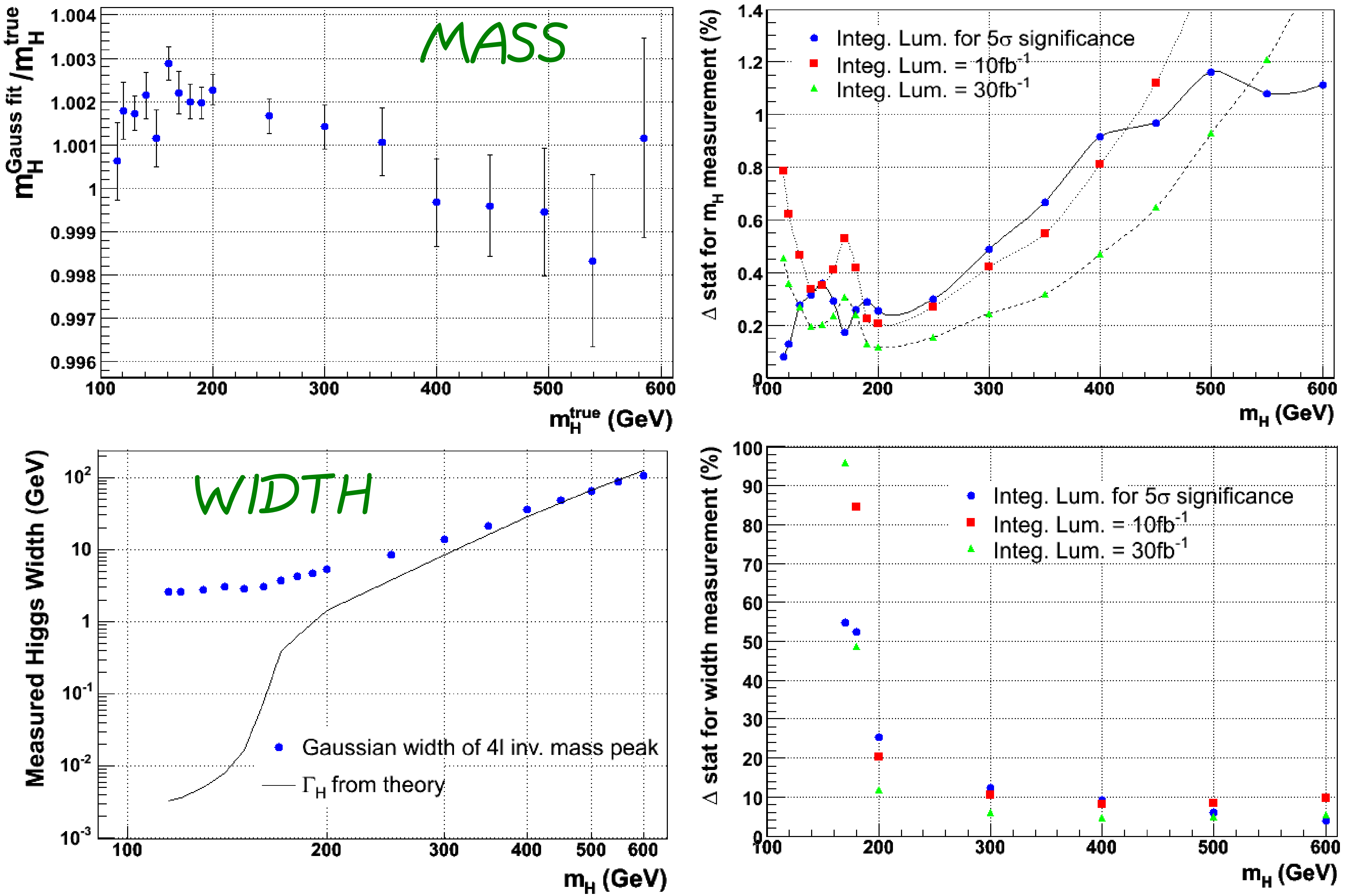
$L = 60\ fb^{-1}$





Higgs properties

from H->ZZ->2e2μ



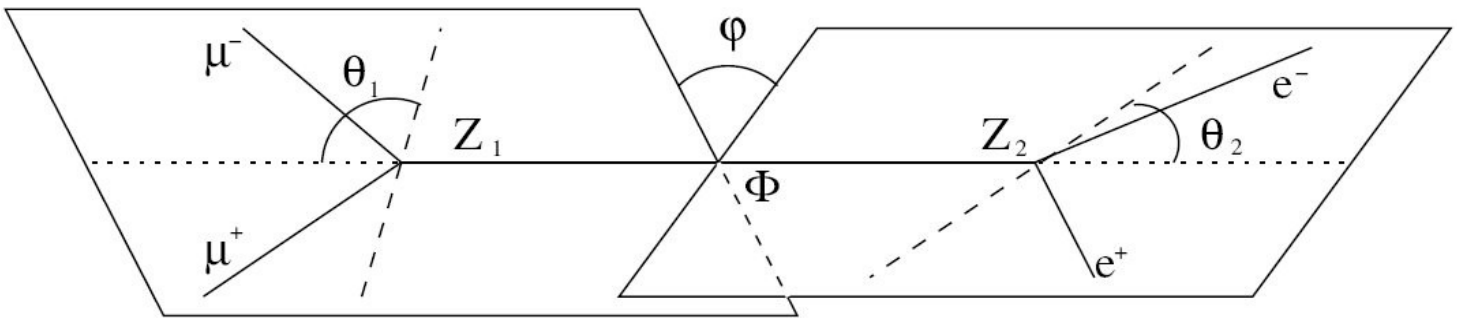
Higgs properties

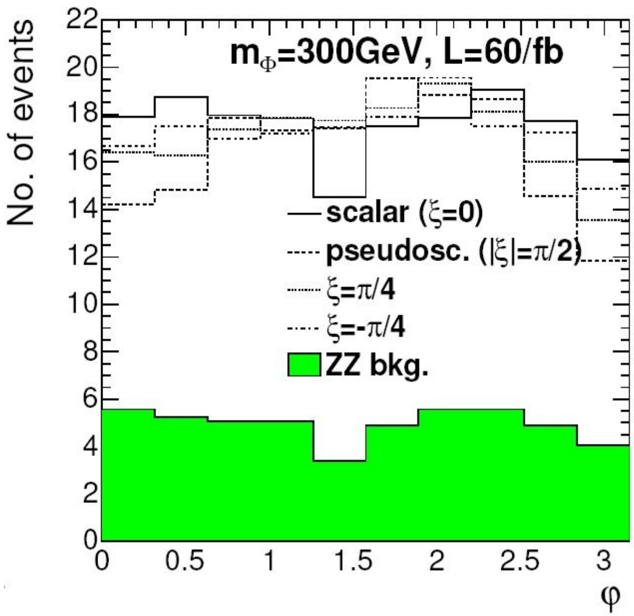
CP Properties

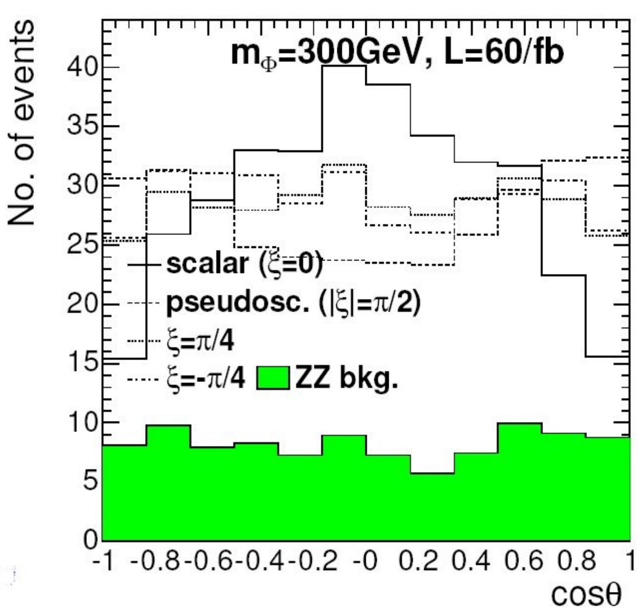
$$C_{\Phi VV} = \kappa \cdot \delta^{\mu\nu} + \frac{\tan(\xi)}{m^2} \cdot \epsilon^{\mu\nu\rho\sigma} k_{1\rho} k_{2\sigma}$$

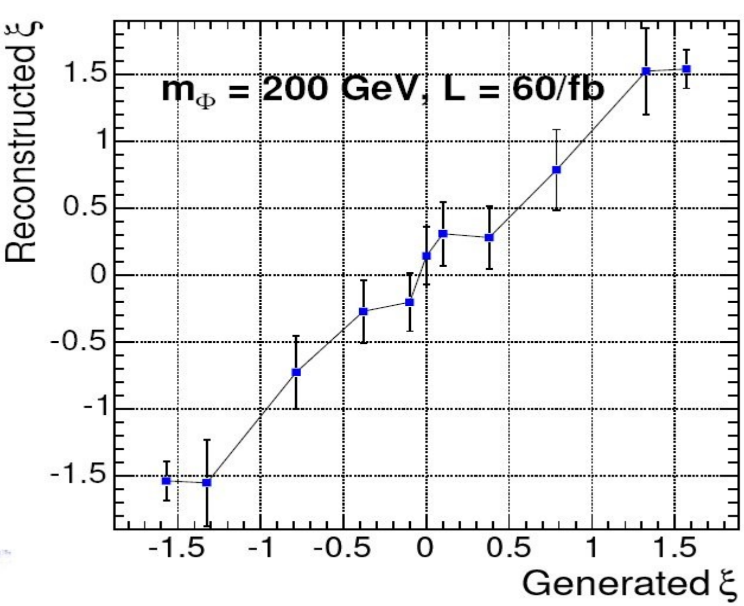
$$d\sigma(\tan(\xi)) \sim H + \tan(\xi) I + \tan(\xi)^2 A$$

Scalar → H; CP violating → I; PseudoScalar → A



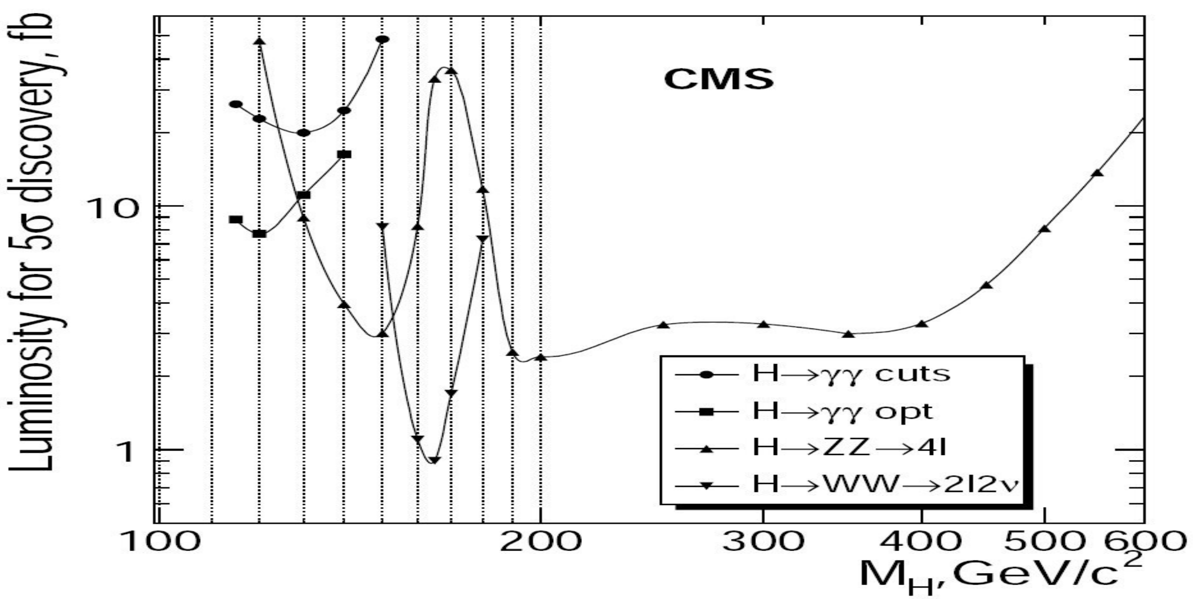




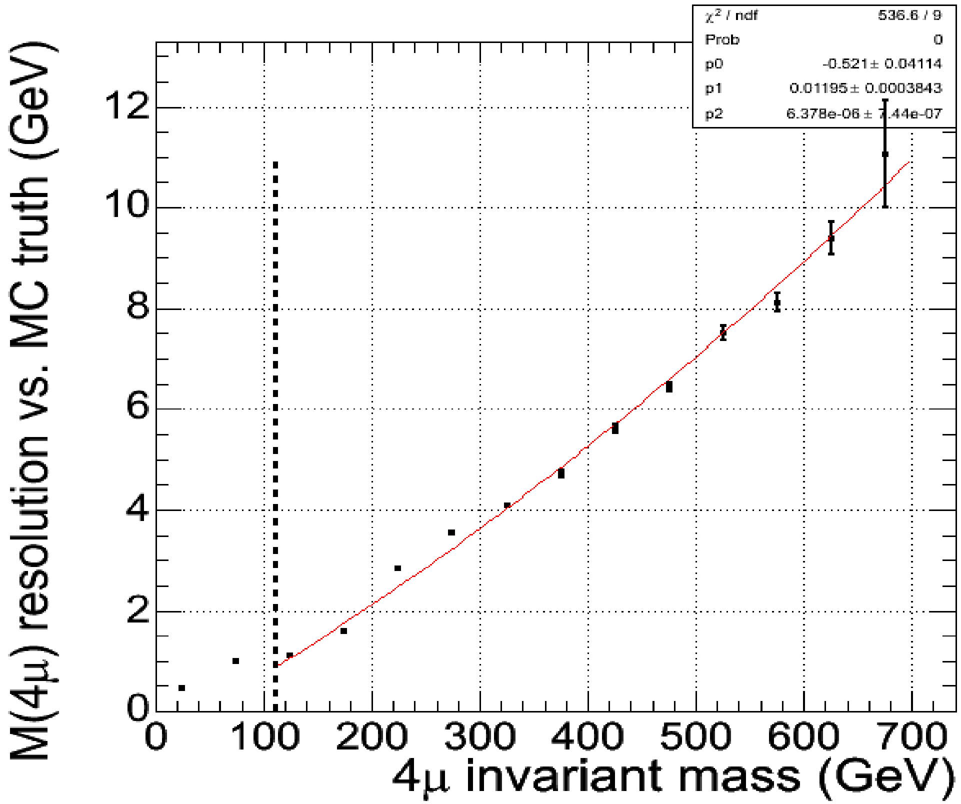


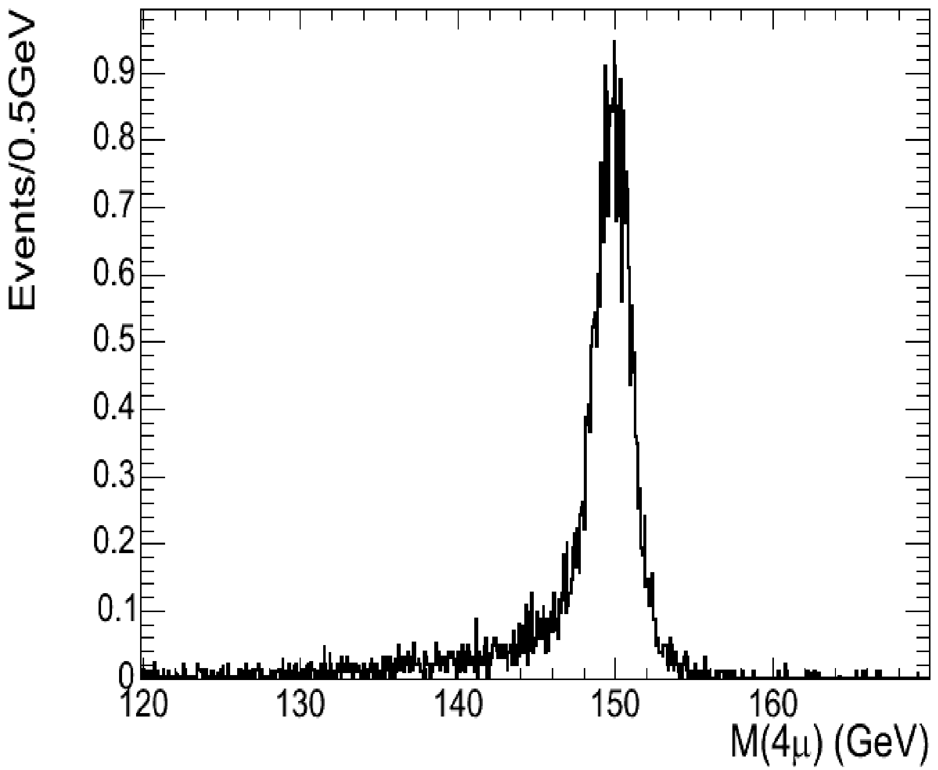
Conclusions

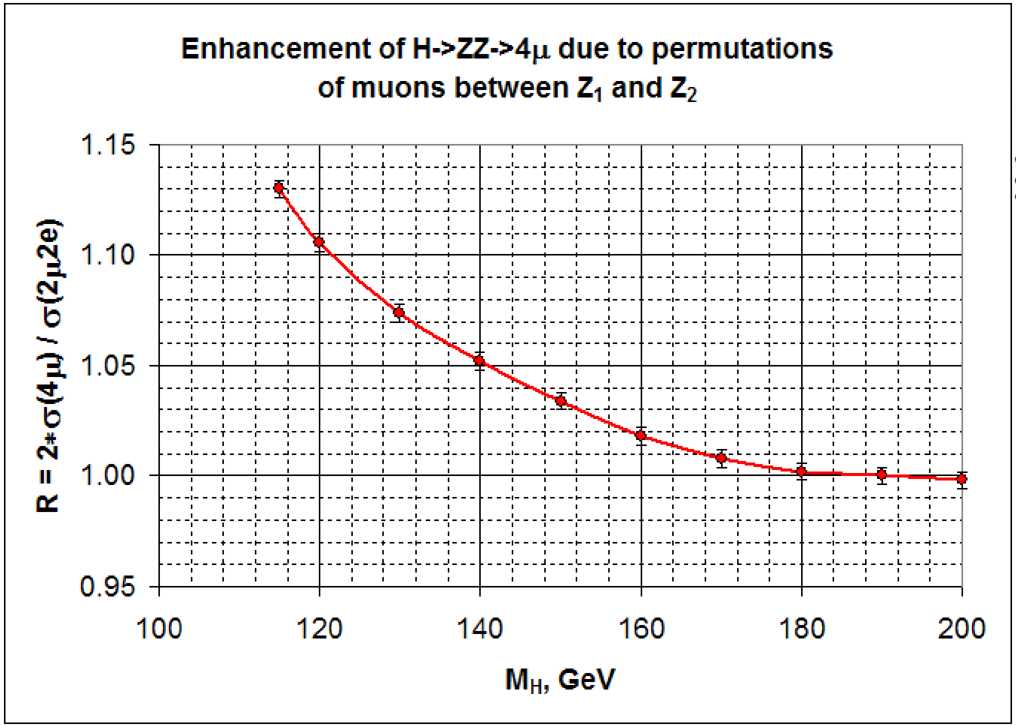
- Most up-to-date full simulation studies show that the Higgs boson can be discovered with ~10 fb^{-1} whatever M_H. For specific mass ranges (~160) even ~1 fb^{-1} could be enough
- Exclusion at 95% can be obtained with 5 fb^{-1} for very low masses and ~1fb^{-1} in the rest of the mass range.
- However, pay attention to the systematic estimation!
- Exclusive channels not suitable for a fast discovery but useful as confirmation and for exploring Higgs properties
- Mass resolution ~0.1% for M_H. Width resolution below natural width only above 200 GeV. CP properties for higher luminosity



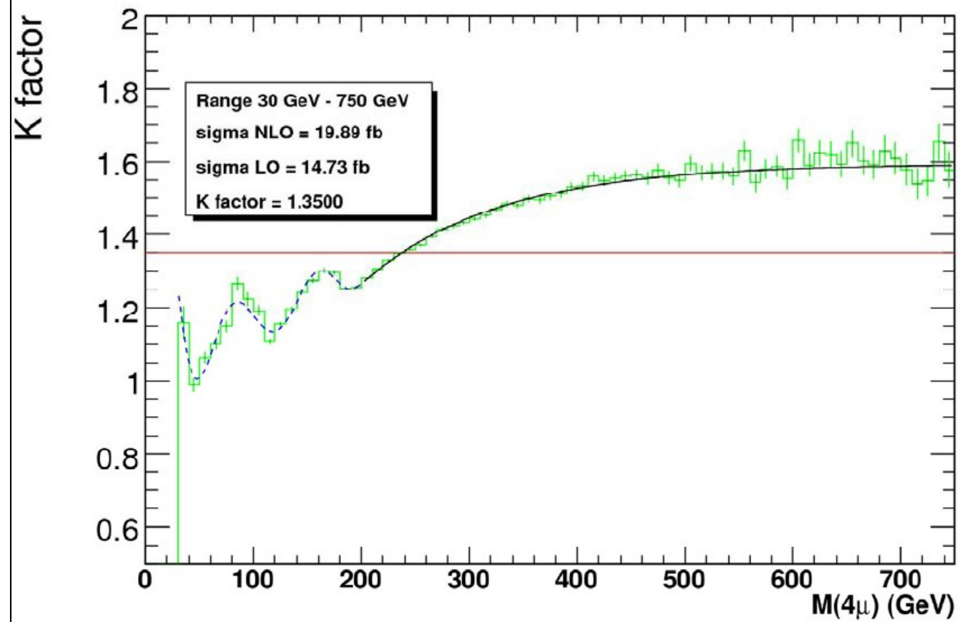
BAK UPs


χ2 / ndf 536.6 / 9
Prob 0
p0 -0.521 ± 0.04114
p1 0.01195 ± 0.0003843
p2 6.378e-06 ± 7.44e-07
M(4μ) resolution vs. MC truth (GeV)
4μ invariant mass (GeV)
0
2
4
6
8
10
12
0
100
200
300
400
500
600
700

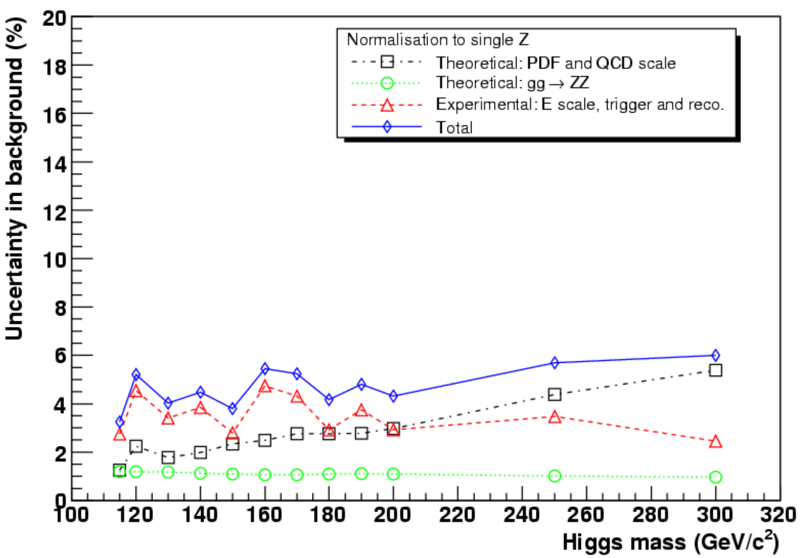

Events/0.5GeV
M(4μ) (GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
120
130
140
150
160



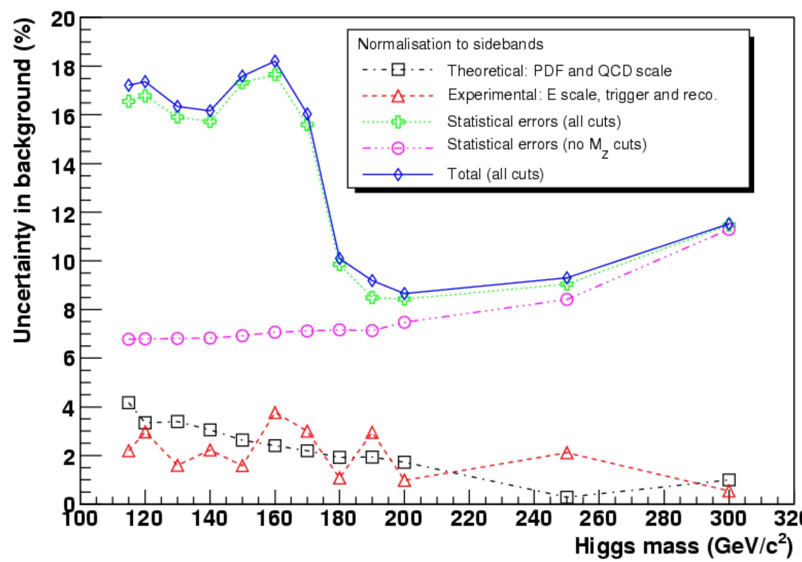
Enhancement of H->ZZ->4μ due to permutations
of muons between Z1 and Z2
R = 2*σ(4μ) / σ(2μ2e)
M_H, GeV



K factor
Range 30 GeV - 750 GeV
sigma NLO = 19.89 fb
sigma LO = 14.73 fb
K factor = 1.3500
M(4μ) (GeV)

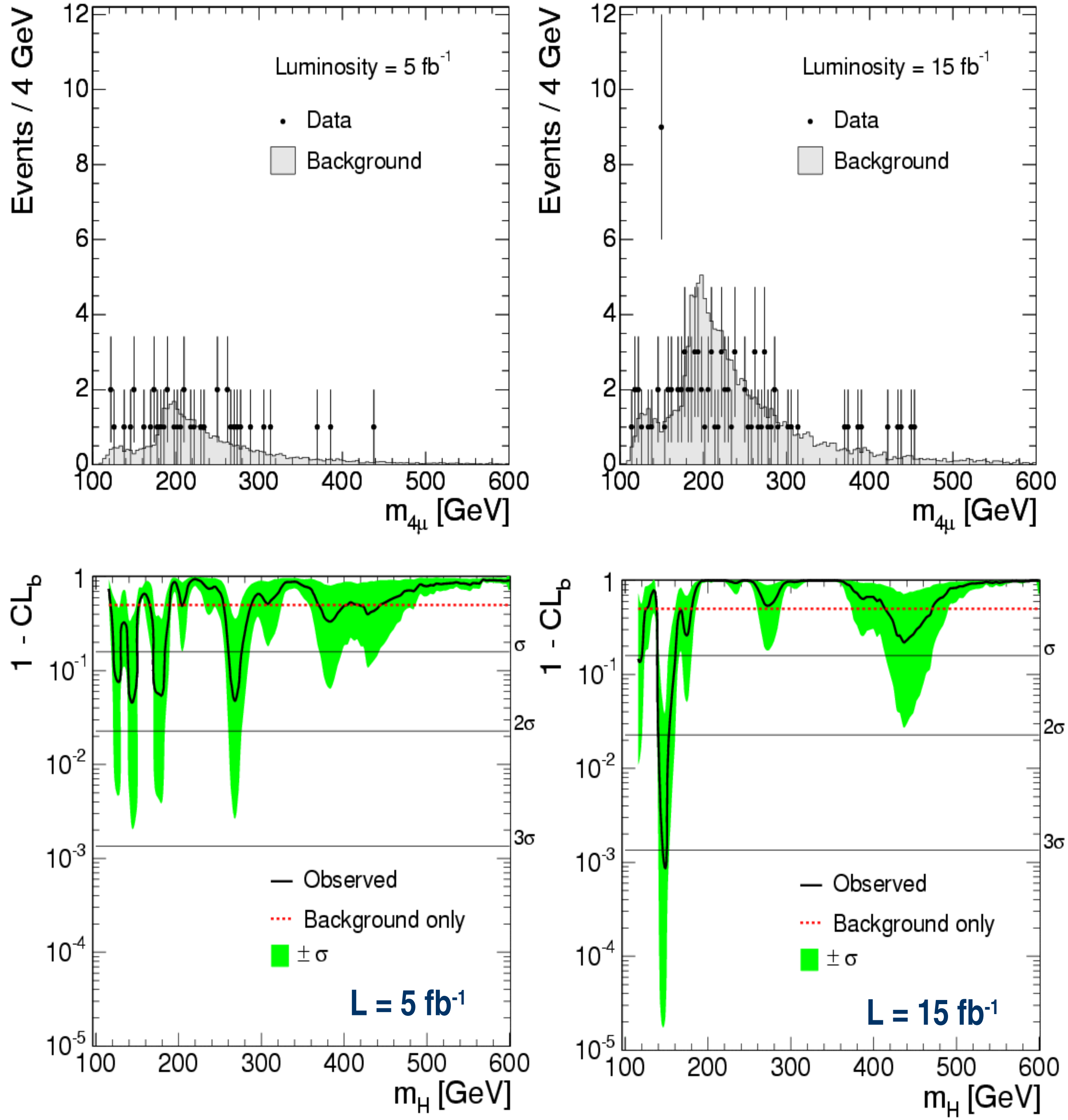


Uncertainty in background (%)
Normalisation to single Z
Theoretical: PDF and QCD scale
Theoretical: gg → ZZ
Experimental: E scale, trigger and reco.
Total
Higgs mass (GeV/c²)



Uncertainty in background (%)
Normalisation to sidebands
Theoretical: PDF and QCD scale
Experimental: E scale, trigger and reco.
Statistical errors (all cuts)
Statistical errors (no M_Z cuts)
Total (all cuts)
Higgs mass (GeV/c²)

- $m_{4\mu}$ distributions for randomly selected pseudo-experiments ('data') with the expected statistics for $L = 5 fb^{-1}$ and $L = 15\ fb^{-1}$, assuming $m_H = 150$ GeV
- $1\text{-}CL_b$ distributions show how incompatible with the B-only hypothesis are data:
  - Low significance over the background expectation for $L = 5fb^{-1}$
  - Higher significance (above 3σ) after accumulating 10 fb^{-1} more



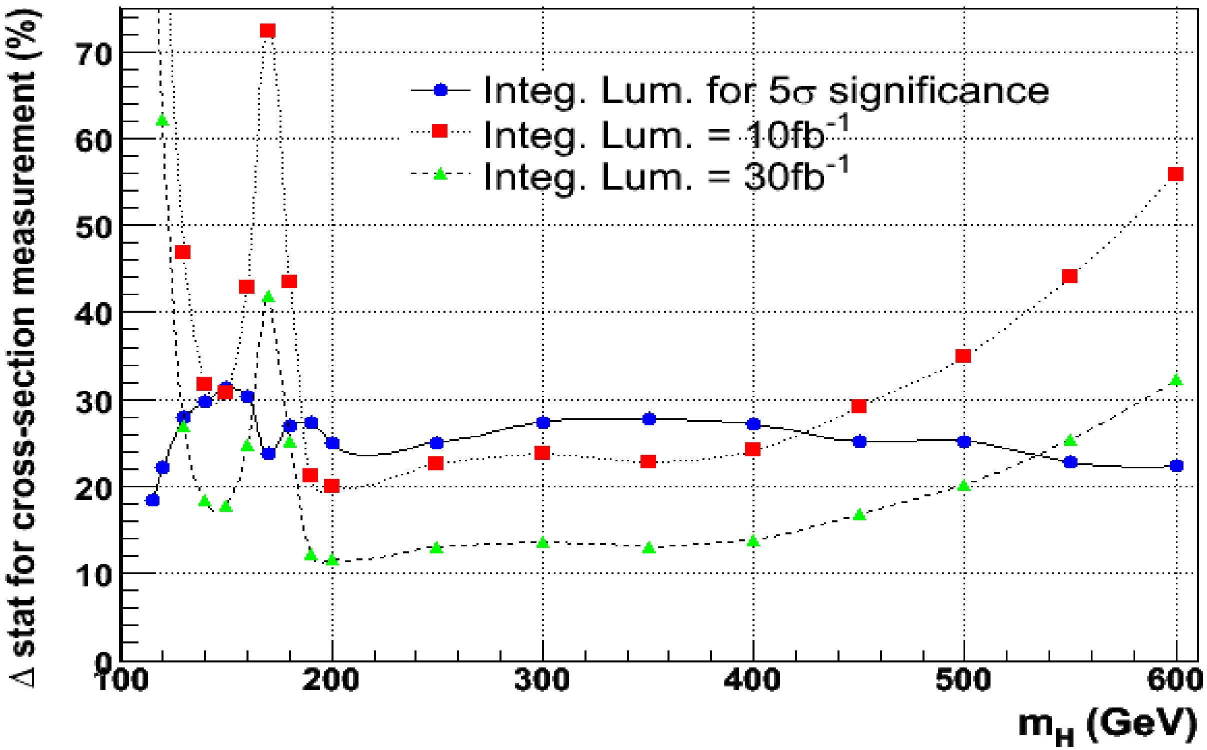
Likelihood Ratio: $Q = \frac{\text{Probability}(s+b)}{\text{Probability}(b)}$

Significance Estimator: $S = \sqrt{2\ln Q}$

One-bin LLR (counting experiment, S_{cL}) $2\ln Q = 2\ln \frac{\frac{(s+b)^n}{n!} e^{-(s+b)}}{\frac{b^n}{n!} e^{-b}} = 2n\ln(1 + s/b) - 2s$

Binned LLR (S_L) $2\ln Q = 2\sum_{bins}\left(n_i \ln(1 + s_i / b_i) - 2s_i\right)$

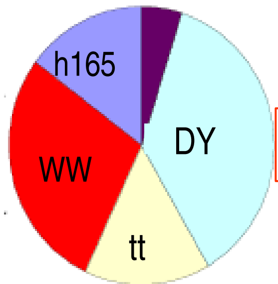
Unbinned LLR (S_L) $2\ln Q = 2\sum_{events}\ln\left(\frac{pdf_{S+B}(m_i)}{pdf_B(m_i)}\right)$



Integ. Lum. for 5σ significance
Integ. Lum. = 10fb-1
Integ. Lum. = 30fb-1
Δ stat for cross-section measurement (%)
0
10
20
30
40
50
60
70
100
200
300
400
500
600
mH (GeV)

WW control region

- $\Delta\phi$ between muons > 0.8
- 50 GeV < Muon Invariant Mass < 80 GeV



WW control region

Number of events

(L = 1 fb^{-1})

Channel	Signal region	WW region	$t\bar{t}$(WW) region	DY (WW) region
Signal	**14.3**	6.0	0.0	0.1
$t\bar{t}$	2.6	6.2	24.7	3.2
WW	5.1	**11.5**	0.0	4.4
DY	0.3	15.0	0.0	267
Wt,ZZ,WZ	0.8	1.9	0.1	7.3
all	23.1	40.6	24.8	282

tt(WW) control region

- JET veto removed
- 2 b-tagged jets

DY(WW) control region

- 80 GeV < $m_{\mu1\mu2}$ < 100 GeV

$$\frac{N^{MC}_{signal_{reg}}}{N^{MC}_{control_{reg}}} = \frac{11.5}{5.1}$$

$$N_{control_{reg}} = N_{tot} - N_{tt} - N_{DY} - N_{Wt,ZZ,WZ} - N_{h165} \Rightarrow N_{signal_{reg}} = 5.1 \ (*)$$

$$N_{control_{reg}} = N_{tot} - N_{tt} - N_{DY} - N_{Wt,ZZ,WZ} \Rightarrow N_{signal_{reg}} = 7.3$$

(*) removing the signal contamination

Systematic error

uncertanty on the composition of *tt(WW)* control region

	Syst. Error	Stat. Error	**Total Error**
(L = 1 fb^{-1})	20 %	20 %	**28 %**
(L = 5 fb^{-1})	15 %	9 %	**17 %**

uncertanty on the composition of *DY(WW)* control region

	Syst. Error	Stat. Error	**Total Error**
(L = 1 fb^{-1})	5 %	6 %	**8 %**
(L = 5 fb^{-1})	5 %	3 %	**6 %**

***WW* control region: dominant error from statistics**

	Err. tt(WW)	Err. DY(WW)	Sys. WW	Sys. Wt	Sys. ZW	Sys. ZZ	**Bkg ±Err.**	**Bkg±Err.** (*)
(L = 1 fb^{-1})	28 %	8 %	9 %	40 %	20 %	20 %	7.3±3.0 (**41%**)	5.1±3.0 (**60%**)
(L = 5 fb^{-1})	17 %	6 %	9 %	40 %	20 %	20 %	36.8±7.8 (**21%**)	25.5±7.8 (**21%**)

(*) removing the signal contamination

Ref (*DY(WW)*): T.Sjostrand et all , Comp. Phys. Comm. 135 (2001)

Ref. *WW*: V. Drollinger, CMS NOTE 2005/024